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Multi-Level Modeling of Socio-Technical Systems

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ABSTRACT

There is an enormous range of computational models and simulations for addressing a variety of analysis and design issues in complex systems. This report addresses systems where behavioral and social phenomena are significant elements of system performance. The report begins with an overview of the state of the art for multi-level modeling of such "socio-technical" systems. It then reports on an interview study of how four non-defense industries address computational modeling of complex aerospace, automotive, building equipment, and semi-conductor systems. The report concludes with several observations on the overall study of which this work was an element.

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INTRODUCTION

The Department of Defense has made enormous investments over several decades in developing computational models and simulations for complex military systems ranging from weapon platforms to operational military organizations. The result has been an estimated 8,000 software artifacts, totaling approximately 10,000,000 lines of code, for roughly $10 billion dollars in investment. Not surprisingly, DoD would like to reuse these assets to address new questions. Consequently, the Assistant Secretary of Defense (R&E) requested the effort summarized by the following Terms of Reference for the Dynamic Multi-Leveling Modeling Framework (DMMF).

SUMMARY OF TERMS OF REFERENCE

"I request the Modeling and Simulation Coordination Office (MSCO) lead a study to investigate how a single or limited number of modeling and simulation (M&S) framework(s) could be developed to allow models from the engineering to theater level to more easily interoperate. The purpose of the study is to determine if it is possible to develop a tool-set to enable senior DoD leaders to evaluate the effects of new or modified military systems, capabilities, force structure, or tactics across a range of scenarios, systems, and fidelities. The goal is an analysis capability with the following characteristics:

- *A single framework (or small number of frameworks) that allows interoperability of various tool sets*
- *Operates at all levels of analysis from Engineering to Theater*
  - *Simultaneous operation of deterministic and stochastic models*
  - *Incorporates the range of models from physics-based to behavioral and social*
- *Allows composability, so the analysis can be quickly reconfigured to address a range of options.*
- *Permitting users to modify parameters at any combination of levels and examine systems / capability trades*
- *Is operable from desktop or single location"*

SUMMARY OF REPORT

This report begins with an overview of the state of the art for multi-level modeling of socio-technical systems. It then reports on an interview study of how four non-defense industries address computational modeling of complex aerospace, automotive, building equipment, and semiconductor systems. The report concludes with several observations of on the overall DMMF study of which this work was an element.

Socio-technical systems involve behavioral and social aspects of people and society that interact with technical aspects of organizational structure and processes -- both engineered and natural -- to create organizational outcomes and overall system performance. These types of systems are often also characterized as complex adaptive systems where independent agents pursue their individual objectives while learning and adapting to evolving system structures and behaviors.

Design and evaluation of such systems can be addressed using the multi-level modeling framework shown in Figure 1. This framework explicitly represents the different levels of abstraction underlying system behaviors and performance. People can only execute work practices that are supported by delivery operations, which only exist if the organizations within the system structure invest in and sustain these capacities, which they will only do if the domain ecosystem incentivizes and rewards the outcomes of these investments.

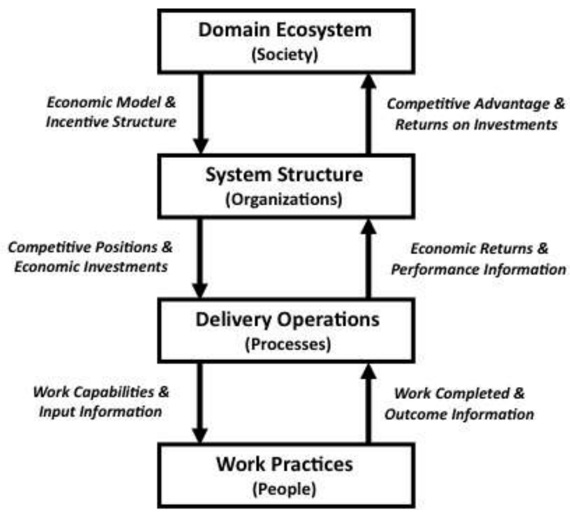

Figure 1. Multi-Level Modeling Framework

The domain ecosystem – society – defines the objectives for the system and the rules of the game. This includes explicit or implicit specification of what matters, what can and cannot be done, and how performance is rewarded. These specifications incentivize or impede organizational decisions.

These decisions include the nature of system capacities considered, levels of investments in these capacities, and assessments of subsequent performance. In this way, delivery operations are created and sustained. They also may be impeded as, for example, government price controls can lead to disinvestment in capacities.

Delivery operations provide capacities for work. These capacities can include engineered systems (e.g., networks and databases, devices and platforms), processes (e.g., procedures, plans), and venues (e.g., factories, playing fields). Work practices or activities, at the bottom of Figure 1, can include physical manipulation (e.g., lifting, carrying, controlling), information provision (e.g., informing, advising) or social interaction (e.g., talking, performing).

The four levels in Figure 1 represent different levels of abstraction. Within each level, there can also be levels of aggregation, as illustrated by Figure 2. For example, individuals, teams, specialties (e.g., electricians) or whole workforces can perform work. Processes can be specific sets of steps, generic sequences of functions, or composite procedures for all automobiles or patients. Organizations can be departments, divisions, subsidiaries or whole corporations. The "grain sizes" of the networks at each level reflect the level of aggregation of the representation of the phenomena at that level.

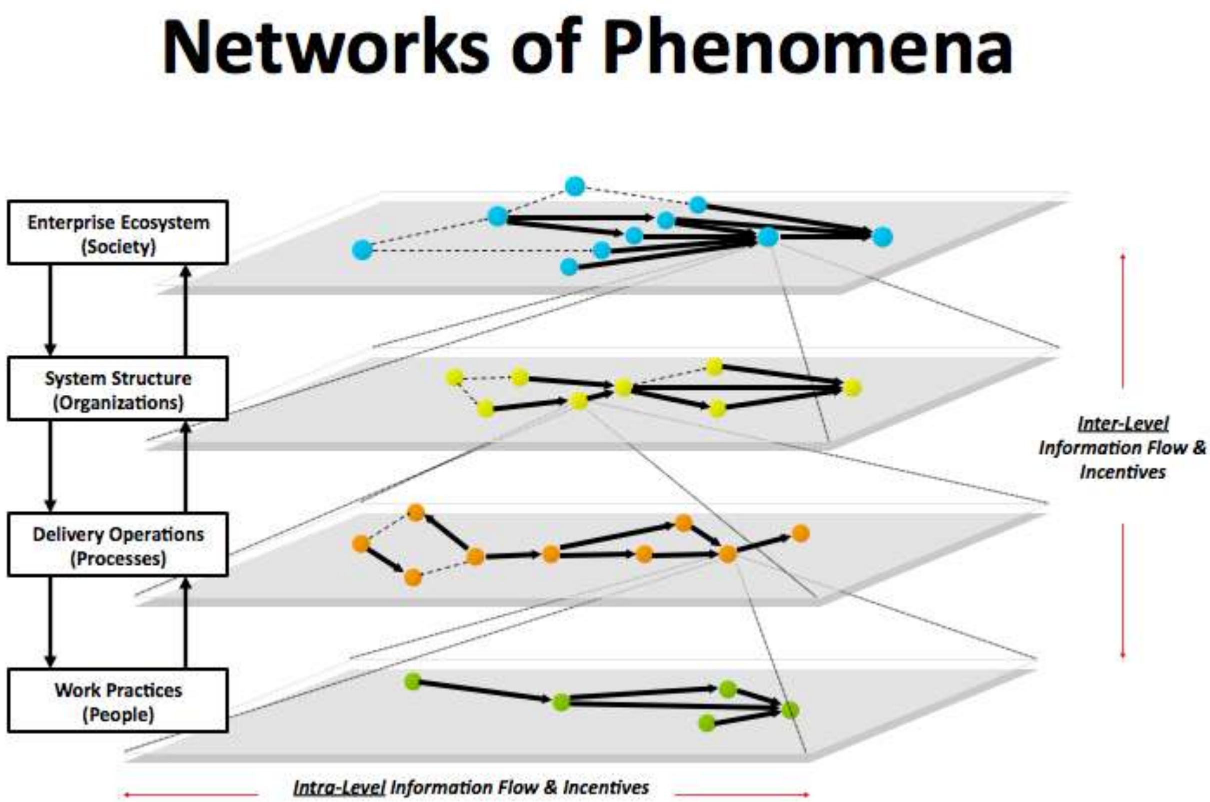

Figure 2. Networks of Phenomena at Each Level

There can be a range of socio-technical phenomena represented in Figures 1 and 2. At the people level, the phenomena of interest are usually human behavior and performance -- individually, in teams, or in groups. For the process level, the central socio-technical phenomenon is the social networks that enable processes. The organization level is typically concerned with economic decision making, drawing upon classical microeconomics or, more recently, behavioral economics. A good example of socio-technical phenomena at the ecosystem level is the evolution of social and cultural norms. There is a rich set of mathematical and computational models that can be drawn upon to represent the range of phenomena outlined here.

Table 1 shows how the multi-level modeling framework can be applied in three different domains. Application of the framework involves representing the phenomena at each level, choosing models to represent these phenomena, selecting computational means to operationalize these models across levels, including the flow of information, e.g., on incentives, within and between levels as indicated in Figure 2. All of these components provide the "engine" for developing interactive visualizations to enable exploration of alternative system designs at multiple levels, e.g., process designs vs. policy rules.

Level	Healthcare Delivery	Energy Consumption	Military Operations
Domain Ecosystem	Social Priorities, Medicare/Medicaid	Public Service Commission	Military Priorities, Rules of Engagement
System Structure	Providers, Payers, Suppliers	Utilities, Builders, Contractors	Commanders, Service Components
Delivery Operations	Care Capabilities, Health Information	Generation, Trans, & Distribution	Strategies, Tactics, Battle Plan
Work Practices	Patient-Clinician Interactions	End-User Consumption	Movement of Forces, Platforms, Etc.

Table 1. Comparison of Domains

The resulting interactive, computational model can be termed a "policy flight simulator." Such simulators can provide the means to explore a wide range of possibilities, thereby enabling the early discarding of bad ideas and refinement of good ones. This enables "driving the future before writing the check." One would never develop and deploy an airplane without first simulating its behavior and performance. However, this happens all too often in organizational decision making in terms of policies, strategies, plans, and management practices that are rolled out with little, if any, consideration of higher-order and unintended consequences.

Complex engineered and natural systems can be characterized as complex adaptive systems where independent, yet interdependent, intelligent agents pursue their goals, often in conflict with other agents, and learn and adapt to the changing ecosystem. A multi-level approach to computationally modeling the functioning of such systems can provide the means to understanding and then transforming these systems.

SURVEY OF INDUSTRY PRACTICES

The issues raised in the Terms of Reference are not unique to the Department of Defense. Other, non-defense industries associated with the design, development, deployment, operation and sustainment of complex systems face these issues as well. This section reports on a series of interviews of eight executives in four industries – automobile, commercial aerospace, building equipment, and semiconductors and electronics. The results of these interviews provide insights that are likely to be of value as the DMMF initiative proceeds

Methodology

The process began with email contact of senior executives in the four industries. These executives held positions ranging from Chief Technology Officer, to Vice President for R&D, to Chief Scientist. Typically, these emails led to electronic introductions to the people appropriate for interviews. The body of the email was as follows:

"I am a member of an advisory panel to the Assistant Secretary of Defense for Research and Engineering. Our task is to assess the state of the art in multi-level modeling in general and model composition in particular. The overarching question concerns the prospects of connecting computational models developed at different times for different purposes to answer new questions such as the impacts of new technological capabilities or perhaps new operational policies.

One of my assignments is to assess how this need is met in non-defense industries such as commercial aircraft, automobiles and semiconductors. I would like your help to find people in your industry that can help me understand how they go about combining legacy models into composite models for addressing new questions. I expect that this is easiest for models of physical systems such as an engine or circuit board, and gets more difficult when looking at whole vehicles, or manufacturing of systems or subsystems. My sense is that this is most challenging when behavioral and social phenomena are central to system performance.

This endeavor also raises questions of "curation" of computational models, including assumption management when creating composite models. The value of legacy models would seem to depend heavily on how these issues are managed. I am also interested in how your industry handles such issues.

If you do not know of someone in your industry who works in the area of combining legacy models, it would still be helpful for me to speak with someone who is a thought leader in modeling complex systems to gain an understanding of important issues and unmet needs.

Thank you in advance for helping me to find some people to talk with about these issues."

Subsequent telephone interviews were scheduled. Each interview was roughly 30 minutes in length. The central questions asked were as follows:

To what extent is composition of legacy models an issue for you?

What types of models are composed?

What socio-technical phenomena are included? Operations? Maintenance? Manufacturing?

Who else do you recommend we contact?

All of the interviews evolved into open-ended discussions. Interview notes were captured in written form and then edited into electronic form.

Results of Interviews

Table 2 provides a summary of the interview results. All of these four industries use modeling and simulation at multiple levels of abstraction. These is, however, little computational linkages of these representations. This is due in part to the allocation of responsibilities and resources across organizational functions. There is recognition that a solution composed of a set of local optima may not represent the globally optimal solution, but these large companies have difficulty approaching their design and development activities in other than a reductionist manner.

All of these companies consider socio-technical phenomena to be important to the success of their systems. Thus, they address human behavior and performance, social and organizational interactions and economic decisions making, e.g., for airline managers and building managers. However, these models are seldom computationally integrated with the physics-based models of the technology components of their systems.

These companies invest in modeling and simulation capabilities because they intend to manufacture hundreds, thousands, or millions of the systems they design. Further, they are responsible for the consequences of design inadequacies or failures. Modeling and simulation helps them to make better choices, and understand the consequences of these choices.

For the most part, they all employ commercially available software (i.e., Matlab, Simulink, Model Center) as their computational engines, with their system representations being their proprietary information. They approach reuse of models with caution, in particular being wary of "model-induced design flaws." They impose standards on tools, software and documentation. Nevertheless, they report that cross-functional negotiations on models and simulations are quite common.

Observations

The overall DMMF study focused on the possibility of addressing new issues associated with complex systems by composing computational models originally developed for different purposes into an overall computational tool. This is a very difficult problem that involves many issues beyond whether two disparate pieces of software can be plugged together and run appropriately.

A particularly difficult aspect of such an endeavor concerns assuring that the sets of assumptions associated with the elements of the composition are compatible. These concerns range from units of measure to coordinate systems to assumptions regarding environmental factors, independence of computations, etc. All of these considerations affect the validity of any composition.

Industry	Companies	Levels of Modeling & Simulation	Human Phenomena	How Models Are Composed	Re-Use Standards
Automobile	General Motors Toyota	Automobile or drivetrain Performance Operations (driver) Traffic (intra vehicle)	Drivers Passengers Assemblers Maintainers	Focused reuse Proprietary representations Commercial computations	Design for reuse Compatible abstractions & assumptions
Commercial Aerospace	Boeing Pratt & Whitney	Aircraft or engine Performance Operations (e.g., range) Market (e.g., routes)	Pilots Passengers Assemblers Maintainers Owners	Product line reuse Proprietary representations Commercial computations	Standards for work, software
Building Equipment	Carrier Otis	Elevator or AC Control system Human demand Building evacuation Energy consumption	Residents Customers Managers	Focused reuse Proprietary representations Commercial computations	Standards for design tools, software & documentation
Semiconductors & Electronics	Freescale Multek	Semiconductor Circuit Device System (e.g., cell phone)	Assemblers	Product line reuse Proprietary representations Commercial computations	Embodied in vendor-provided software tools

Table 2. Multi-Level Modeling Across Industries

The status quo in DoD is that such composition is accomplished, but very slowly and very expensively. The real time composition capabilities requested in the Terms of Reference are rarely available. Non-defense industries do have some of these capabilities. However, investments in such capabilities have been limited to situations where these investments can be amortized across large numbers of units produced.

To the extent that "plug and play" of models is possible -- and meaningful -- the component models have usually been designed to be composed, in contrast to being re-purposed from pieces not originally meant for composition. Design for re-use often involves adopting standards for software development and documentation.

It should also be noted that the time and money required for DoD to compose models for new purposes are not solely due to the difficulty of the technical problem. DoD business processes for securing resources and requesting permissions have been found, at least in some cases, to consume the majority of the time and money.

CONCLUSIONS

The problem of composing disparate computational models into composite tools for addressing new problems is pervasive across DoD and non-defense industries. It is very difficult to assure the validity of the resulting combination.   The bottom line is that "plug and play" is immensely difficult without standards for code, documentation, etc. When the consequences are sufficient, however, this capability is feasible.